

IMPROVED PERFORMANCE OF A TEMPERATURE COMPENSATED LN₂ COOLED SAPPHIRE OSCILLATOR*

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Abstract

We report on improved stability in a whispering gallery sapphire resonator for which the dominant WGH_{n11} microwave mode family shows frequency-stable, compensated operation for temperatures above 77K. Several modifications during the past year have led to significant improvements in performance. Current tests with improved thermal stability provide Allan Deviation of frequency of $2.6 - 4 \cdot 10^{-13}$ for measurement times of $1 \leq \tau \leq 100$ seconds. We project a frequency stability of 10^{-14} for this resonator with stabilized housing temperature and with a mode Q of 10^7 .

Introduction

Improved ultra-stable frequency standards such as JPL's Linear Ion Trap Standard (LITS) are necessary to meet radio science requirements for future NASA/JPL missions [1]. To meet all mission stability requirements, the local oscillator steered by the trapped ion discriminator must have an Allan Deviation of better than 5×10^{-14} for $1 \leq \tau \leq 100$ seconds. The best available crystal quartz oscillator performance is no better than 1×10^{-13} for $1 \leq \tau \leq 100$ seconds.

Cryogenic superconducting or sapphire oscillators [2-5] achieve the desired performance, but are complex and expensive to maintain due to their operation at liquid helium temperature (~4.2K). High stability is achieved because the temperature coefficients of expansion and dielectric constant are 'frozen out' at this temperature. A cryogenic oscillator operating at liquid nitrogen (LN₂) temperature or above could be a simpler, less expensive and more compact solution. A mechanical compensation of the temperature coefficients of expansion and dielectric constant has the capability to provide the stability necessary for the LITS's future

local oscillator.

Methodology

A traditional whispering-gallery mode resonator, as in Figure 1 (top), has an intrinsic quality factor (Q) of about 30 million at 77K and provides excellent phase noise performance when used to stabilize a crystal quartz oscillator [6-7]. The frequency stability, however, is poor due to the temperature coefficients of expansion and dielectric constant in the sapphire.

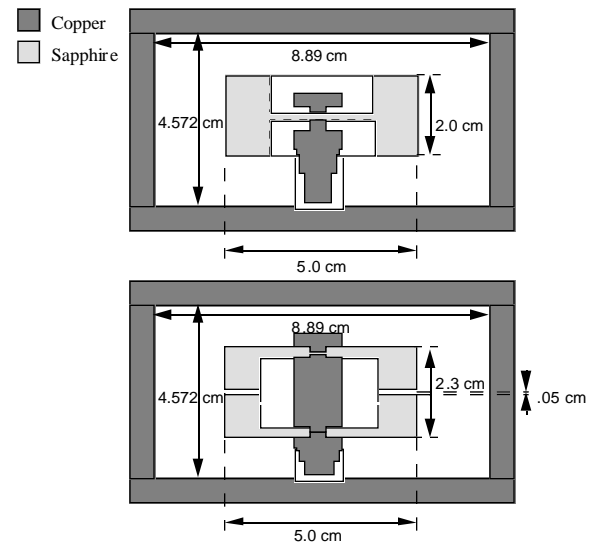


Figure 1. Top resonator is a typical whispering-gallery mode resonator which has poor frequency stability at LN₂ temperature due to temperature fluctuations. The bottom resonator's frequency is temperature compensated at ~87K - the expansion of the copper increases the gap spacing between the sapphire elements which counteracts the effect of the expansion and increase in dielectric constant in the sapphire.

The solution for mechanical compensation is a sapphire-copper composite structure, as in Figure 1 (bottom), in which a split sapphire resonator is separated by a copper post [7-8]. Increasing temperature, which would tend to decrease resonant frequency, causes the copper post to expand separating

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the sapphire elements, thereby increasing the vacuum gap and causing an increase in frequency. At a certain operating temperature these effects completely cancel, and therefore compensate the resonator frequency for temperature variation.

Sources of Frequency Instability

We have identified several significant sources of frequency instability during the development of our compensated sapphire resonator stabilized oscillator. Vibration sensitivity is a concern because of the multiple element structure of our resonator. No deliberate quantitative testing and analysis was performed to determine vibration sensitivity, but during initial tests the system was subjected to vibration and impulses. Several mechanical resonances were observed in the range $1\text{ kHz} < f < 10\text{ kHz}$ with ringing times of less than a second. These are not expected to degrade frequency stability performance as the resonator's response and vibration induced noise level were no greater than those seen in the traditional type sapphire resonator or the crystal quartz oscillator.

Flicker noise in the rf system components are limiting factors in the completed system. We therefore employ the lowest noise components available and design for the shortest microwave path lengths possible.

Temperature fluctuations and gradients in the system are the largest contributors to poor stability performance. We achieve a thermal time constant in the composite resonator of less than five seconds (unit responds as a single thermal mass) for operation of the compensation mechanism.. A thermal time constant of 300 seconds between cavity and resonator allows the compensated resonator to provide temperature compensated ultra-stable performance if not impaired by the rest of the system.

A frequency lock loop gain of 100 is required to achieve a stability of 10^{-13} with a VCO of stability 10^{-11} . Insufficient loop gain is seen as a turn up in frequency stability at short averaging times in the upper two curves of Figure 2..

Previous Status

Previously reported performance results were obtained using a compensated resonator as in Figure 1. In experimental tests, the WGH_{811} mode showed a frequency turn-over temperature of 87K in agreement with finite element calculations. Tests of oscillator operation show an Allan Deviation of frequency variation of $1.4 - 6 \cdot 10^{-12}$ for measuring times $1 \leq \tau \leq 100$ seconds with unstabilized resonator housing temperature and a mode Q of $2 \cdot 10^6$. These first stability results

for such a compensated sapphire resonator stabilized oscillator are seen in the first (top) graph of Figure 2. Further experiments have discovered several limitations in the original system design. Over the past year several modifications have been made to the system which have steadily improved stability performance.

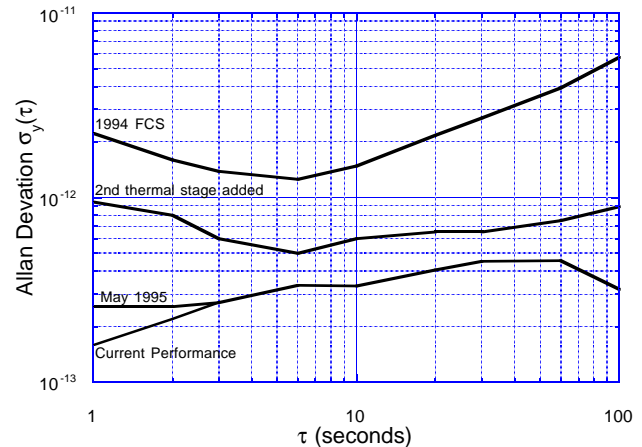


Figure 2. Allan Deviation of the compensated sapphire resonator oscillator presented at last years symposium, after addition of a thermal isolation stage, after Pound circuit and various other modifications (May 1995), and current performance.

Modifications for Improvement

Resonator and Cavity Thermal Stability

The performance limit reported in last year's proceedings (Figure 2) was found to be limited by thermal stability of the resonator containment can. The copper can cavity which houses the resonator was thermally well anchored to the LN_2 bath. Changes in room temperature and pressure as well as the LN_2 level effect the temperature of the liquid nitrogen bath. These temperature fluctuations, which are well followed by the resonator housing, limit Allan Deviation performance to parts in 10^{-12} . An isolation stage with a long thermal time constant was added to dampen the effect of the LN_2 temperature fluctuations on the resonator cavity.

The design, as shown in Figure 3, is re-entrant to minimally effect the resonator's placement in the cryostat. The original bottom plate with the copper center that sits in the LN_2 bath is spaced approximately 8mm from the copper can, but the thermal path length is approximately 6.5cm. The thermal isolation stage is composed of a stainless steel 'deep dish' in which a copper cylinder is attached. On top of the copper

cylinder is a stainless steel plate which only makes contact to the copper can with a ~0.5cm width ring at its outer radius. The copper cylinder has thermistors and a heater element which allow the temperature of the stage to be controlled.

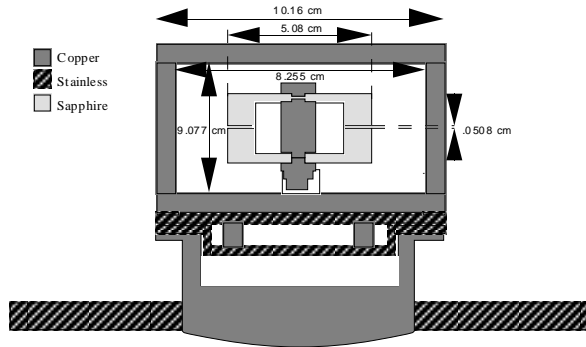


Figure 3. Resonator can with added thermal isolation stage.

First tests with the stabilized resonator housing temperature achieved Allan Deviation of frequency variation of $5 - 6 \cdot 10^{-13}$ for measuring times $5 \leq \tau \leq 30$ seconds, and better than 10^{-12} for all measurement times between 1 and 100 seconds. The resonator operated at its turnover temperature (~87K), the new isolation stage was a few degrees above the LN_2 temperature, and there was no servo control of either of the heaters during the experiment resulting in the second graph of Figure 2. The stability of the current sources used to drive the heaters was found to be poor, so they were replaced with more stable supplies for subsequent experiments.

Pound Circuit Modifications

The first two graphs in Figure 2 show a degradation for $\tau < 5$ seconds due to insufficient loop gain in the frequency lock circuitry. The resonator is frequency locked to a 100 MHz crystal quartz voltage controlled oscillator using a Pound circuit as in Figure 4. Previous experiments used a 50-200 kHz phase modulation frequency injected into the VCO input. The frequency multiplier frequency lock circuitry loses its lock to the VCO at modulation frequencies greater than 200 kHz. Therefore we modified the multiplier to allow injection of a 2 MHz modulation frequency into its phase modulation input. This increase in loop gain in the frequency lock circuitry greatly improved stability performance and, as can be seen in the third graph of Figure 2, the slope from $\tau = 1-5$ seconds was eliminated.

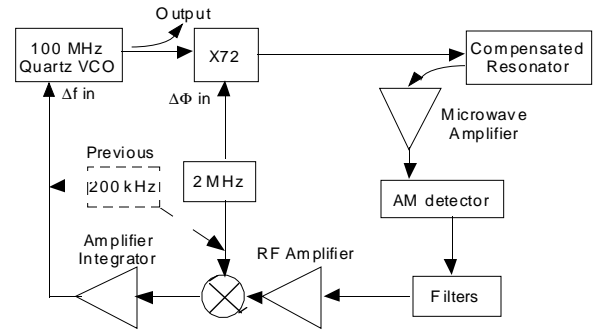


Figure 4. Previous Pound (frequency lock) circuit limited to a 200 kHz modulation frequency. To increase loop gain, circuit modified to allow a 2 MHz modulation frequency.

Other Improvements

Increasing the loop gain proves to be the significant factor in achieving the May 1995 performance, but several other improvements contribute to the oscillator's stability. The resonator is the only component of the system contained in the cryostat. The external microwave components are exposed to the environment of our open laboratory. These mixers, hybrids, amplifiers, connectors, and cable lengths are sensitive to temperature fluctuations and in combination greatly contribute to the instability of the system. By insulating the microwave components, including the Pound circuitry, with foam, the system reaches a more stable operating temperature.

Another effect is temperature fluctuations and gradients on the relatively long coaxial line which feeds the resonator in the cryostat. It is at LN_2 temperature at the resonator and room temperature at the cryostat's input making it sensitive to LN_2 and room temperature fluctuations. This instability is reduced by better isolating the line from the cryostat wall and maintaining a more stable LN_2 surface temperature and level. This improvement noticeably helps provide the May 1995 stability in Figure 2.

Monitoring various temperatures in the system, we found that the sapphire temperature followed the outer can as well as showing its own temperature fluctuations. This indicated a thermal 'leak' in the resonator. The thermal path was a combination of a small vacuum leak and thermal radiation. Sealing the leak and adding radiation shielding significantly improved short term stability as seen in the current performance in Figure 2.

Future Work

Several additional improvements have been identified as necessary to achieve the desired oscillator stability. The resonator's thermal environment is currently free running and not actively controlled. Addition of feedback control electronics to the heater elements of the system with better than milliKelvin temperature resolution is required for the desired ultra-stable performance.

Temperature sensitivity of the microwave components continues to be a concern, and so it may be advantageous to move the microwave components closer to the resonator (perhaps in the cryostat) to reduce the path length of the microwave signals.

A significant improvement in stability will come with increased resonator Q. The current resonator Q for the compensated mode used is 2-3 million, while other modes in the resonator show Q's of 20 million. This is due to losses from poor surface cleanliness of the sapphire, especially in the gap where the compensated mode is most sensitive. An improved sapphire cleaning and assembly procedure should allow us to achieve resonator Q's of 7-8 million. The calculated noise limit performance at a Q of 8 million is 10^{-14} compared to $3 \cdot 10^{-14}$ for our current Q.

Conclusion

We have demonstrated a new USO capability with a 6-10x improvement over the past year. Stabilities of $2.6 \cdot 10^{-13}$ for $1 \leq \tau \leq 200$ seconds have been demonstrated in our laboratory. We predict stabilities of $7 \cdot 10^{-14}$ for $1 \leq \tau < 200$ seconds in the near future and $\sim 1 \cdot 10^{-14}$ for $1 \leq \tau < 200$ seconds with a resonator Q of 8 million.

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